US009182760B2

(12) **United States Patent**
Braunstein et al.

(10) **Patent No.:** **US 9,182,760 B2**
(45) **Date of Patent:** **Nov. 10, 2015**

(54) **METHOD OF MANAGING A WORKSITE**

(71) Applicant: **Caterpillar Inc.**, Peoria, IL (US)

(72) Inventors: **Michael Braunstein**, Washington, IL (US); **Ramadev Hukkeri**, Pittsburgh, PA (US); **Michael Taylor**, Swissvalve, PA (US)

(73) Assignee: **Caterpillar Inc.**, Peoria, IL (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 26 days.

(21) Appl. No.: **13/712,417**

(22) Filed: **Dec. 12, 2012**

(65) **Prior Publication Data**

US 2014/0163773 A1      Jun. 12, 2014

(51) **Int. Cl.**
| | |
|---|---|
| G05D 1/00 | (2006.01) |
| G05D 3/00 | (2006.01) |
| G06F 7/00 | (2006.01) |
| G06F 17/00 | (2006.01) |
| G06F 7/70 | (2006.01) |
| G06F 19/00 | (2011.01) |
| G06G 7/00 | (2006.01) |
| G06G 7/76 | (2006.01) |
| G05D 1/02 | (2006.01) |
| E02F 9/20 | (2006.01) |
| E02F 9/26 | (2006.01) |

(52) **U.S. Cl.**
CPC ............... *G05D 1/021* (2013.01); *E02F 9/205* (2013.01); *E02F 9/2054* (2013.01); *E02F 9/265* (2013.01); *G05D 2201/0202* (2013.01)

(58) **Field of Classification Search**
CPC ............................... A01B 73/00; A01B 69/008
USPC ....................................................... 701/2, 50
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

| | | | | |
|---|---|---|---|---|
| 6,246,932 | B1 * | 6/2001 | Kageyama et al. | ............. 701/24 |
| 7,680,639 | B2 | 3/2010 | Schoeggl | |
| 2006/0164295 | A1 | 7/2006 | Focke et al. | |
| 2009/0306866 | A1 | 12/2009 | Malikopoulos | |
| 2010/0076708 | A1 * | 3/2010 | Hukkeri et al. | .................. 702/94 |
| 2010/0076709 | A1 * | 3/2010 | Hukkeri et al. | .................. 702/94 |
| 2013/0079948 | A1 * | 3/2013 | Hsu et al. | ........................... 701/1 |

OTHER PUBLICATIONS

Ramadev Hukkeri et al, "Vehicle Model Calibration System for a Mobile Machine", filed Jun. 30, 2011 for U.S. Appl. No. 13/173,341.
Ramadev Hukkeri et al., "Vehicle Model Calibration System for a Mobile Machine", filed Dec. 28, 2011 for U.S. Appl. No. 13/338,859.
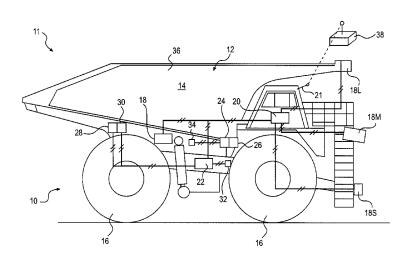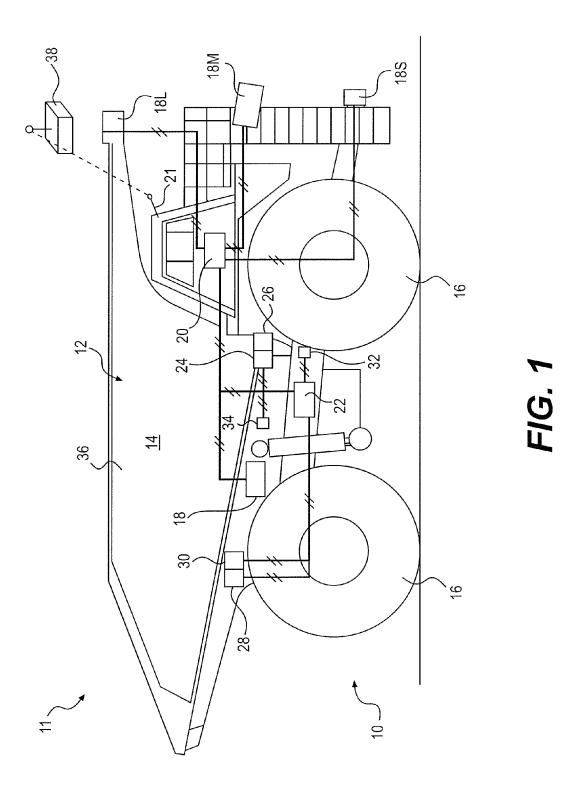
* cited by examiner

*Primary Examiner* — Imran Mustafa
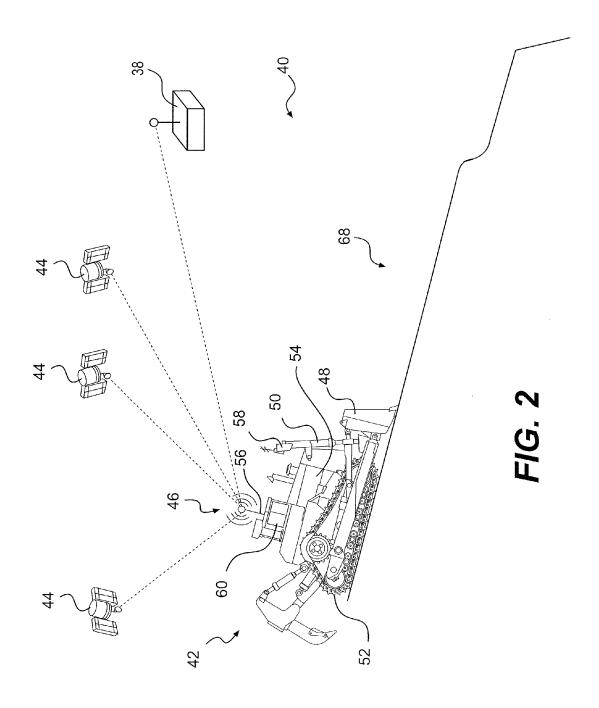(74) *Attorney, Agent, or Firm* — Finnegan, Henderson, Farabow, Garrett & Dunner, LLP

(57) **ABSTRACT**

A method is disclosed for calibrating a vehicle model used to autonomously control a machine on a worksite. The method may include measuring a first value indicative of an operating condition of the machine, predicting a second value, using the vehicle model, corresponding to the first value and indicative of the operating condition, and determining a difference between the first value and the second value. The method may also include autonomously directing the machine to a calibration site of the worksite in response to determining that the difference between the first value and the second value is greater than a predetermined threshold, wherein the calibration site is automatically selected from a plurality of locations at the worksite based on a suitability index of the calibration site.
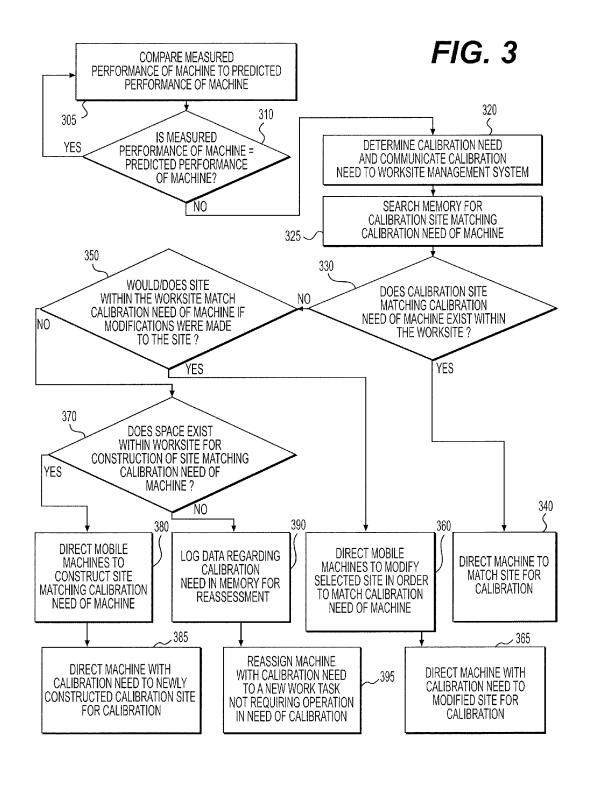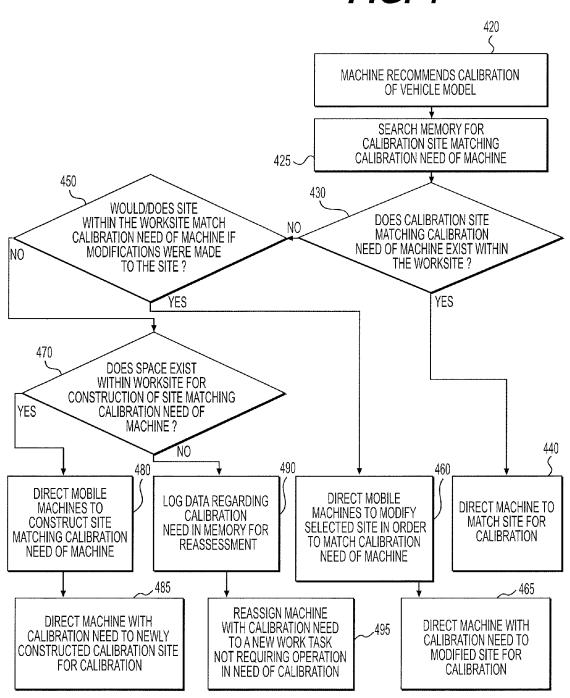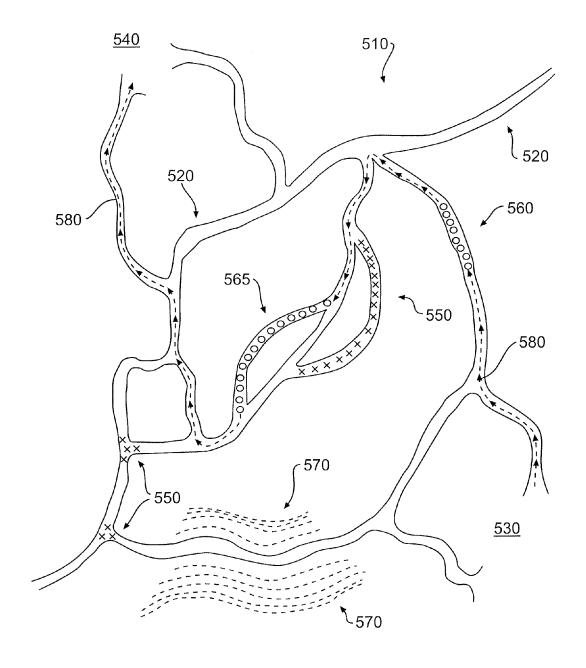
**18 Claims, 5 Drawing Sheets**

*FIG. 1*

*FIG. 2*

*FIG. 3*

COMPARE MEASURED
PERFORMANCE OF MACHINE TO PREDICTED
PERFORMANCE OF MACHINE

305

YES

310

IS MEASURED
PERFORMANCE OF MACHINE =
PREDICTED PERFORMANCE
OF MACHINE?

NO

320

DETERMINE CALIBRATION NEED
AND COMMUNICATE CALIBRATION
NEED TO WORKSITE MANAGEMENT SYSTEM

325

SEARCH MEMORY FOR
CALIBRATION SITE MATCHING
CALIBRATION NEED OF MACHINE

350

WOULD/DOES SITE
WITHIN THE WORKSITE MATCH
CALIBRATION NEED OF MACHINE IF
MODIFICATIONS WERE MADE
TO THE SITE ?

NO

NO

330

DOES CALIBRATION SITE
MATCHING CALIBRATION
NEED OF MACHINE EXIST WITHIN
THE WORKSITE ?

YES

YES

370

DOES SPACE EXIST
WITHIN WORKSITE FOR
CONSTRUCTION OF SITE MATCHING
CALIBRATION NEED OF
MACHINE ?

YES

NO

380

DIRECT MOBILE
MACHINES TO
CONSTRUCT SITE
MATCHING CALIBRATION
NEED OF MACHINE

390

LOG DATA REGARDING
CALIBRATION
NEED IN MEMORY FOR
REASSESSMENT

DIRECT MOBILE
MACHINES TO MODIFY
SELECTED SITE IN ORDER
TO MATCH CALIBRATION
NEED OF MACHINE

360

340

DIRECT MACHINE TO
MATCH SITE FOR
CALIBRATION

385

DIRECT MACHINE WITH
CALIBRATION NEED TO NEWLY
CONSTRUCTED CALIBRATION SITE
FOR CALIBRATION

REASSIGN MACHINE
WITH CALIBRATION NEED
TO A NEW WORK TASK
NOT REQUIRING OPERATION
IN NEED OF CALIBRATION

395

365

DIRECT MACHINE WITH
CALIBRATION NEED TO
MODIFIED SITE FOR
CALIBRATION

# FIG. 4

420

```
MACHINE RECOMMENDS CALIBRATION
OF VEHICLE MODEL
```

425

```
SEARCH MEMORY FOR
CALIBRATION SITE MATCHING
CALIBRATION NEED OF MACHINE
```

450

WOULD/DOES SITE
WITHIN THE WORKSITE MATCH
CALIBRATION NEED OF MACHINE IF
MODIFICATIONS WERE MADE
TO THE SITE ?

430

DOES CALIBRATION SITE
MATCHING CALIBRATION
NEED OF MACHINE EXIST WITHIN
THE WORKSITE ?

NO

NO

YES

YES

470

DOES SPACE EXIST
WITHIN WORKSITE FOR
CONSTRUCTION OF SITE MATCHING
CALIBRATION NEED OF
MACHINE ?

YES

NO

```
DIRECT MOBILE
MACHINES TO
CONSTRUCT SITE
MATCHING CALIBRATION
NEED OF MACHINE
```

480

```
LOG DATA REGARDING
CALIBRATION
NEED IN MEMORY FOR
REASSESSMENT
```

490

```
DIRECT MOBILE
MACHINES TO MODIFY
SELECTED SITE IN ORDER
TO MATCH CALIBRATION
NEED OF MACHINE
```

460

440

```
DIRECT MACHINE TO
MATCH SITE FOR
CALIBRATION
```

485

```
DIRECT MACHINE WITH
CALIBRATION NEED TO NEWLY
CONSTRUCTED CALIBRATION SITE
FOR CALIBRATION
```

```
REASSIGN MACHINE
WITH CALIBRATION NEED
TO A NEW WORK TASK
NOT REQUIRING OPERATION
IN NEED OF CALIBRATION
```

495

465

```
DIRECT MACHINE WITH
CALIBRATION NEED TO
MODIFIED SITE FOR
CALIBRATION
```

540

510

520

520

580

560

580

565

550

550

570

570

530

**FIG. 5**

# METHOD OF MANAGING A WORKSITE

## TECHNICAL FIELD

The present disclosure relates generally to a method of managing a worksite and, more particularly, to a method of managing machine calibration.

## BACKGROUND

Autonomous worksites are designed to provide productivity gains through more consistency in processes. Such worksites may employ a plurality of autonomous machines such as, for example, off-highway haul trucks, motor graders, and other types of heavy equipment to perform a variety of tasks. Primary operation of such machines may be controlled by a combination of on-board and off-board computers, processors, and other electronic controllers rather than human operators. As a result, autonomous operation may enhance the productivity of the machines, and reduce the human resources required for controlling the operation of the worksite.

To operate the autonomous machines safely and efficiently on the worksite, the machines are usually equipped with sensors for detecting objects on the worksite. For example, RADAR (radio detection and ranging) sensors, SONAR (sound navigation and ranging) sensors, LIDAR (light detection and ranging) sensors, IR (infrared) and non-IR cameras, and other similar sensors may be used. The sensed objects may include specific geographical features of the worksite (for example, berms, markers, rocks, etc.), the other machines on the worksite, and any obstructions on the worksite. The machines are also generally equipped with sensors for detecting information regarding characteristics of the machine itself (for example, engine speed, travel and/or work speed, steering angle, transmission gear or gear ratio, orientation such as pitch and roll, geographical location, load weight, and load distribution). A vehicle model, which is a computer model that is used in autonomous operation of the machine on the worksite, may be stored in a computer memory of the machine. Processors on-board the machine may receive outputs from the sensors and, using the vehicle model, may predict how the machine will operate, for example, given its current speed and steering angle, and/or future drive commands of the machine. In the event the processors predict that the machine should not continue on its current course (for example, the processors predict the machine will collide with a sensed object if the machine maintains its current steering angle), the processors may also use the vehicle model to determine what changes should be made, and to predict whether these changes will, in fact, result in continued safe and efficient operation of the machine.

Periodic calibration of the vehicle model is necessary for desired machine operation since the predicted performance of the autonomous machine may vary substantially from the actual performance of the machine. For example, calibration may be required due to, among other things, a change in worksite conditions, a change in the configuration of the machine, and/or because of wear of components used in the machine.

To perform calibration of the vehicle model, the autonomous machine may undergo a series of specific tests. The tests measure the actual performance of the machine, using the uncalibrated vehicle model, under a variety of conditions, including different loads, speeds, steering angles, and orientations of the machine. After the conclusion of the testing, the actual performance of the machine under the various conditions is compared to the performance that was predicted by the uncalibrated vehicle model under those same conditions. The vehicle model may then be adjusted or calibrated based on the comparison, so that future use of the calibrated vehicle model will result in the actual operation of the autonomous machine being substantially the same as the predicted operation of the machine.

An exemplary calibration system and method is described in U.S. Patent Publication No. 2006/0164295 (the '295 publication) by Focke et al. published on Jul. 27, 2006. Specifically, the '295 publication describes a system for simultaneous calibration of two different types of sensors, for example, an image sensor and a radar sensor mounted on a motor vehicle. During calibration of the two sensors, the motor vehicle is aligned in front of a calibration object in such a way that the image and radar sensors detect reference features of the calibration object and responsively create calibration data. The calibration data is used directly for calibration of the participating sensors. For example, the calibration data is used for automatic correction of a deviation of a sensor axis in relation to a vehicle longitudinal axis or by an automotive technician for mechanical adjustment of sensor placement. These procedures are possible during manufacture or repair of the motor vehicle.

Although the sensor system of the '295 publication may be helpful in calibrating machine-mounted sensors, the benefit may be limited as there are a number of different types of vehicle model calibration that may be necessary in order for an autonomous work machine to operate efficiently. For example, different loads, speeds, steering angles, and orientations of the machine may all be parameters that require calibration and/or recalibration during the lifetime of the autonomous machine.

Challenges to calibrating an autonomous work machine vehicle model may include, for example, the need for an autonomous machine to be transported to an area designated specifically for calibration-related activity. The designated area may be a significant distance from the autonomous worksite. The size of the designated area may limit the number of machines undergoing vehicle model calibration at any particular time. Further, it may take a significant amount of time to complete all of the specific tests required for complete calibration of the vehicle model. Thus, the autonomous machine may not be available to perform any task on the autonomous worksite for a relatively long period of time, until the vehicle model is completely calibrated and the autonomous machine is transported to the worksite. Subsequent recalibration of the vehicle model may result in similar disadvantages, since it may be necessary to transport the autonomous machine back to the designated area to again undergo the series of specific tests.

The disclosed systems and methods are directed to overcoming one or more of the problems set forth above and/or other problems of the prior art.

## SUMMARY

The disclosure may provide a method for calibrating a vehicle model used to autonomously control a machine on a worksite. The method may include measuring a first value indicative of an operating condition of the machine, predicting a second value, using the vehicle model, corresponding to the first value and indicative of the operating condition, and determining a difference between the first value and the second value. The method may also include autonomously directing the machine to a calibration site of the worksite in response to determining that the difference between the first

value and the second value is greater than a predetermined threshold, wherein the calibration site is automatically selected from a plurality of locations at the worksite based on a suitability index of the calibration site.

The disclosure may further provide a method of calibrating a vehicle model used to autonomously control a machine on a worksite. The method may include measuring a first value indicative of an operating condition of the machine, predicting a second value, using the vehicle model, corresponding to the first value and indicative of the operating condition, and determining a difference between the first value and the second value. The method may also include providing a signal to a worksite management system in response to determining the difference between the first value and the second value is greater than a predetermined threshold, wherein the worksite management system is disposed remote from the machine and the signal is indicative of an aspect of the vehicle model that is in need of calibration. The method may further include autonomously directing the machine to a calibration site of the worksite in response to receipt of the signal by the worksite management system, wherein the calibration site is automatically selected by the worksite management system from a plurality of locations at the worksite based on a suitability index of the calibration site.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a pictorial illustration of an autonomous machine having an exemplary disclosed vehicle model calibration system;

FIG. 2 is a pictorial illustration of an exemplary worksite management system coordinating the creation of an exemplary calibration path for the machine of FIG. 1;

FIG. 3 is a flow chart illustrating an exemplary worksite management system operation performed for the machine of FIG. 1;

FIG. 4 is a flow chart illustrating an alternate exemplary worksite management system operation performed for the machine of FIG. 1; and

FIG. 5 is a pictorial illustration of an exemplary worksite map generated by the worksite management system.

## DETAILED DESCRIPTION

FIG. 1 illustrates a machine 10 having an exemplary vehicle model calibration system 12 that may calibrate and/or recalibrate a vehicle model used to autonomously control machine 10 on a worksite 11 (FIG. 2). Worksite 11 may include, for example, a mine site, a landfill, a quarry, a construction site, or any other type of worksite known in the art.

Machine 10 may embody an autonomous mobile machine. An "autonomous" machine refers to an unmanned machine that includes on-board and/or off-board computers, processors, and/or other electronic controllers which, based on input from various machine sensors, stored data, and control algorithms, provides outputs to control various machine systems such as steering, braking and propulsion to accomplish desired tasks. For example, an autonomous haul truck may include on-board systems that determine the position and heading of the machine, and control steering, propulsion, and braking to follow a route provided by an off-board path planning system and to avoid obstacles in the machine's path. Semi-autonomous machines may provide some functions that are controlled by the on-board and off-board systems, while allowing an operator to control other functions. For example, for a motor grader, the on-board controller may control the machine to follow a route, while the operator

controls the implement or blade. Machine 10 may include, for example, an earth moving machine such as an off-highway haul truck, a wheel loader, a motor grader, a fluid delivery truck, or any other mobile machine known in the art. Machine 10 may further include, among other things, a power source 15, and a body 14 supported by one or more traction devices 16.

Power source 15 may include an engine such as, for example, a diesel engine, a gasoline engine, a gaseous fuel powered engine such as a natural gas engine, or any other type of engine apparent to one skilled in the art. Power source 15 may alternatively include a non-combustion source of power such as a fuel cell, a power storage device, an electric motor, or other similar mechanism. Power source 15 may be connected to traction devices 16 via a direct mechanical coupling, an electric circuit, a hydraulic circuit, or in any other suitable manner.

On-board controller 20 may cause machine 10 to autonomously follow a route generated by a path planner associated with worksite 11. Machine 10 may also include a semi-autonomous or non-autonomous mobile machine. In such cases, a semi-autonomous or non-autonomous machine 10 may receive, from a path planner associated with worksite 11, recommended routes for an operator of machine 10 to consider. The recommended routes may be presented to the operator via a monitor or other electronic display. The operator of a semi-autonomous or non-autonomous machine 10 may evaluate the recommended options presented by the path planner associated with worksite 11 and select a desirable route for machine 10 to follow. A path planner associated with worksite 11 may include a worksite management system 38 which may generate a calibration plan or "calibration roadmap" designating a recommended calibration route 580 (FIG. 5) by which machine 10 may efficiently visit one or more calibration sites 40 within worksite 11 while circumventing calibration excluded (or exclusion) zones 550 (FIG. 5). A calibration exclusion zone 550 may be an area within worksite 11 that is excluded by worksite management system 38 for purposes of calibration. Calibration sites 40 may include road segments within worksite 11 that are adequate for calibration of an aspect of a vehicle model associated with machine 10. Calibration exclusion zones 550 may include road segments on worksite 11 which may include high traffic areas, for example, an intersection or a loading and/or dumping zone. Recommended calibration route 580, calibration sites 40, and calibration exclusion zones 550 will be discussed in greater detail below.

Machine 10 may safely and efficiently autonomously follow recommended calibration routes 580 by relying on data input from one or more sensors 18. As shown in FIG. 1, sensors 18 may be mounted to body 14 and may be used for object detection. The objects detected by sensors 18 may include specific areas on worksite 11, for example, areas at which material is loaded and unloaded, geographical features of worksite 11, other autonomous or human-operator-controlled machines on the worksite, and any obstructions on the worksite. In an exemplary embodiment, machine 10 may be equipped with one or more short range sensors 18S, medium range sensors 18M, and/or long range sensors 18L located at different positions around body 14 of machine 10. Each of sensors 18 (S, M, L) may embody a device that detects the position, configuration, shape, and/or orientation of objects disposed within a sensing range of the sensors 18 (S, M, L). One or more sensors 18 (S, M, L) may include a LIDAR device, a RADAR device, a SONAR device, an IR or non-IR camera device, and/or any other sensing device known in the art. In one possible example, sensors 18 (S, M, L) may include

5

6

an emitter that emits a detection beam and an associated receiver that receives a reflection of that detection beam. Based on characteristics of the reflected beam, a distance and a direction from an actual sensing location of sensors 18 (S, M, L) on machine 10 to a portion of the sensed object may be determined. Sensors 18 (S, M, L) may then generate a position signal corresponding to the distance and direction, and communicate the position signal to on-board controller 20. On-board controller 20 may receive the position signal from sensors 18 (S, M, L) and, using a calibrated vehicle model, may operate machine 10 to avoid a collision with the sensed object. For example, on-board controller 20 may steer machine 10 to the left or right to avoid an object that is detected by sensors 18 (S, M, L).

Machine 10 may also be equipped with one or more sensors 22, mounted at different locations on machine 10, for detecting information regarding one or more conditions of the machine 10, such as a load carried by machine 10, a maintenance state of machine 10, and/or a location of machine 10. In an exemplary embodiment, sensors 22 may include one or more of a speed sensor 24, a steering angle sensor 26, a load weight sensor 28, a load distribution sensor 30, an orientation sensor 32, and a location and heading sensor 34.

Speed sensor 24 may detect an actual ground or travel speed of machine 10 as it moves on worksite 11. The speed of machine 10 may be detected in a variety of ways. For example, speed sensor 24 may detect a number of revolutions over a given time period for a component of a traction device 16, such as a wheel hub, and either speed sensor 24, on-board controller 20, or another processor may determine the speed of machine 10 using this information. In another embodiment, speed sensor 24 may measure an actual distance traveled by machine 10 over a given time period, and either speed sensor 24, on-board controller 20, or another processor may determine the speed of machine 10 based on this information. Speed sensor 24 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the speed of machine 10.

Steering angle sensor 26 may detect an actual steering angle of machine 10. The steering angle may be detected in a variety of ways. For example, steering angle sensor 26 may sense a location, angle, and/or other characteristic of a component of a traction device 16, such as a wheel hub. In another embodiment, steering angle sensor 26 may sense a location, angle, and/or other characteristic of another component of machine 10, such as a rack and/or a pinion when machine 10 is turned by a rack-and-pinion steering system. In that case, a rotation angle of the pinion and/or a translation of the rack may be sensed, and either steering angle sensor 26, on-board controller 20, or another processor may determine the steering angle of machine 10 using this information. Steering angle sensor 26 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the steering angle of machine 10.

Load weight sensor 28 may detect an actual weight of material being hauled by machine 10, in the event machine 10 is configured to haul material on worksite 11. The weight of the load carried by machine 10 may be detected in a variety of ways. For example, load weight sensor 28 may measure decreases in effective lengths of one or more springs supporting a dump box 36 of machine 10, and either load weight sensor 28, on-board controller 20, or another processor may determine the weight of material hauled by machine 10 using this information. Load weight sensor 28 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the weight of material being hauled by machine 10.

Load distribution sensor 30 may detect an actual distribution of the weight of the material being hauled by machine 10. The distribution of the weight hauled by machine 10 may be detected in a variety of ways. For example, load distribution sensor 30 may measure decreases in effective lengths between or among groups of springs supporting dump box 36 of machine 10. By comparing lengths of springs on the front of dump box 36 to lengths of springs on the back of dump box 36, and/or to lengths of springs on the left or right side of dump box 36, either load distribution sensor 30, on-board controller 20, or another processor may determine the distribution of the weight of the material hauled by machine 10 based on such comparisons. Load distribution sensor 30 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the distribution of weight of material being hauled by machine 10.

Orientation sensor 32 may determine an actual orientation of machine 10 on worksite 11. The orientation of machine 10 may include a roll of machine 10, which may be an angle measured about a roll axis that extends generally between a front and a back of machine 10, and/or may include a pitch of machine 10, which may be an angle measured about a pitch axis that extends generally between left and right sides of machine 10. Orientation sensor 32 may directly detect the orientation of machine 10 (e.g., detect the orientation of machine 10 relative to an artificial horizon), or may detect the orientation of an area on the ground that supports machine 10. Either orientation sensor 32, on-board controller 20, or another processor may determine the orientation of machine 10 using this information. Orientation sensor 32 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the orientation of machine 10.

Location and heading sensor 34 may determine an actual geographical location and/or an actual heading of machine 10 on worksite 11. The location and heading of machine 10 may be detected in a variety of ways. For example, sensor 34 may utilize a positioning system, to determine various operating parameters of the machine such as velocity, pitch rate, yaw rate, roll rate, etc. The positioning system may utilize Global Positioning System (GPS) data along with data from an Inertial Measurement Unit (IMU), which typically includes one or more yaw rate sensors such as gyroscopes, to calculate heading. In another embodiment, sensor 34 may include a local position detecting system that indicates the geographical location and/or heading of machine 10 relative to one or more transmitters on the worksite 11. Either sensor 34, on-board controller 20, or another processor may determine the location of machine 10 and/or the actual heading of machine 10 based on this information. Sensor 34 is not limited to a specific location on machine 10, however, and is not limited in the way that it detects the location of machine 10.

The above-described sensors 22 may generate signals corresponding to the detected conditions of machine 10, and may communicate the signals to on-board controller 20. On-board controller 20 may receive the signals from sensors 22 and enter information carried by one or more of the signals into, for example, a memory, a look-up table, a control map, and/or a control algorithm within machine 10 to maintain safe and efficient operation of machine 10 on worksite 11.

On-board controller 20 may include components configured to monitor, record, condition, store, index, process, and/or communicate information received from sensors 18 and sensors 22. These components may include, for example, a memory, one or more data storage devices, one or more processors or central processing units, and/or any other components, including tangible, physical, and non-transitory components (hardware and software), which may be used to

run the disclosed application. Furthermore, although aspects of the present disclosure may be described generally as being stored within a controller memory, one skilled in the art will appreciate that these aspects can be stored on or read from different types of computer program products or non-transitory and tangible computer-readable media such as computer chips and secondary storage devices, including hard disks, floppy disks, optical media, CD-ROM, or other forms of RAM or ROM. On-board controller **20** may communicate with, receive information and/or instructions from, or otherwise be controlled by an automated worksite management system **38** (FIG. **2**), such as Caterpillar Inc.'s MINESTAR SYSTEM™ or other similar systems.

Worksite management system **38** may include components configured to monitor, record, condition, store, index, process, and/or communicate information received from sensors **18**, sensors **22**, and/or on-board controller **20** of all machines **10** at worksite **11**. These components may include, for example, a memory, one or more data storage devices, one or more processors or central processing units, or any other components, including tangible, physical, and non-transitory (hardware and software) components, which may be used to run the disclosed application.

In exemplary embodiments, worksite management system **38** may be in communication with multiple machines **10** and may track respective service-related needs of one or more machines **10**. Any of the data stored by worksite management system **38** may be retrieved and addressed when machine **10** frequents a service center. Such service-related needs may include, for example, tire air pressure, status of tire treads and/or brake conditions. Worksite management system **38** may also record the time of recordation of the various service-related needs. Additionally, worksite management system **38** may schedule routine maintenance for machine **10** and/or may coordinate the repair and maintenance of machine **10** as problems arise.

In addition to service-related needs, worksite management system **38** may also monitor and address calibration-related needs for machine **10**. Calibration-related needs may exist for machine **10** when machine **10** is new and/or after machine **10** has been in use for any particular amount of time. Initially, the vehicle model stored in a computer memory accessible by on-board controller **20** of machine **10** may be uncalibrated. If a vehicle model has been calibrated, over time, it may require recalibration for various reasons. For example, the vehicle model may require recalibration when replacement and/or repair of any part of machine **10** is performed. Worksite management system **38** may store preconfigured calibration needs of machine **10**, and may schedule the occurrence of the calibration needs and their calibration.

In some embodiments, worksite management system **38** may coordinate with and/or otherwise control one or more machines **42** to make modifications to road geometry, road conditions, and/or other aspects of worksite **11** in order to assist in calibrating various vehicle models. Machines **42** may be semi-autonomous or non-autonomous. In such cases, for example, worksite management system **38** may provide the operator of semi-autonomous and/or non-autonomous machines **42** with recommended routes and/or actions that semi-autonomous and/or non-autonomous machines **42** may take to assist in the modification of worksite **11**. Such recommended routes and/or actions may be presented to the operator via a monitor or other electronic display. FIG. **2** illustrates an exemplary machine **42** that may be used to assist in making such modifications to worksite **11**. Machine **42** may embody an earth moving machine such as a dozer having a blade or other work tool **48** movable by way of one or more motors or

actuators **50**. Machine **42** may also include one more traction devices **52** which may function to steer and/or propel machine **42**. Machine **42** may be directed by worksite management system **38** to perform a task related to the preparation of a calibration site **40**. For example, such tasks may include a dozing operation, a grading operation, a leveling operation, a bulk material removal operation, and/or any other type of operation that results in alteration of the current geography and/or road conditions at calibration site **40**.

As illustrated in FIG. **2**, a control system **46** associated with machine **42** may include on-board components that interact to affect operation of machine **42** in response to instructions received from worksite management system **38** and/or positional information received from one or more satellites **44**. In particular, control system **46** may include a power source **54** used to power actuators **50** and traction devices **52**, a locating device **56**, a tool position sensor **58**, and/or an on-board controller **60**. On-board controller **60** may be in communication with power source **54**, actuators **50**, traction devices **52**, locating device **56**, and/or position sensor **58** via multiple different communication links (not shown) to autonomously control operations of machine **42**.

Power source **54** may include an engine such as, for example, a diesel engine, a gasoline engine, a gaseous fuel powered engine such as a natural gas engine, or any other type of engine apparent to one skilled in the art. Power source **54** may alternatively include a non-combustion source of power such as a fuel cell, a power storage device, an electric motor, or other similar mechanism. Power source **54** may be connected to traction devices **52** and/or actuators **50** via a direct mechanical coupling, an electric circuit, a hydraulic circuit, or in any other suitable manner.

Locating device **56** may embody an electronic receiver configured to communicate with satellites **44** to determine a location of machine **42** relative to satellites **44**. In particular, locating device **56** may receive and analyze high-frequency, low power radio signals from multiple satellites **44** to triangulate a 3-D position relative to the different satellites **44**. A signal indicative of this position may then be communicated from locating device **56** to on-board controller **60**. Alternatively, locating device **56** may embody an Inertial Reference Unit (IRU), a component of a local tracking system, or any other known locating device that receives and/or determines positional information associated with machine **42**.

Position sensor **58** may embody any type of sensor configured to detect a position of a work tool **48** relative to a known position on machine **42** (for example, relative to locating device **56**), and generate a corresponding signal. In one example, position sensor **58** may be an acoustic, magnetic, or optical-type sensor associated with actuators **50** and/or one or more linkages that move work tool **48**. In another example, position sensor **58** may be a local and/or global positioning sensor configured to communicate with off-board devices (for example, local laser systems, radar systems, satellites, etc.) to directly determine local and/or global coordinates of work tool **48**. It should be noted that any number and/or type of position sensors **58** may be included and positioned at any location on or near work tool **48**. Based on signals generated by position sensors **58** and based on known kinematics of machines **42**, each on-board controller **60** may be configured to determine, in real time, a location of the associated work tool **48** relative to the known position of machine **42** and communicate the location to on-board controller **60** for further processing.

On-board controller **60** may include components configured to monitor, record, store, index, process, and/or communicate the location of machine **42** and position of work tool

**48.** In addition, such components may be configured to automatically control operations of machine **42** based on instructions received from worksite management system **38**. These components may include, for example, a memory, one or more data storage devices, a central processing unit, or any other components that may be used to autonomously operate machine **42**. Furthermore, although aspects of the present disclosure may be described generally as being stored in memory, one skilled in the art will appreciate that these aspects can be stored on or read from different types of computer program products or computer-readable media such as computer chips and secondary storage devices, including hard disks, floppy disks, optical media, CD-ROM, or other forms of RAM or ROM. Such components may be similar to those described above with respect to on-board controller **20**.

Tool controller **60** may further include components configured for communicating with worksite management system **38**. For example, tool controller **60** may include hardware and/or software that enables sending and receiving of data messages through a direct data link (not shown) or a wireless communication link (not shown). The wireless communications may include satellite, cellular, infrared, and any other type of wireless communications that enable on-board controller **60** to exchange information with worksite management system **38**.

Worksite management system **38**, based on various user inputs and location information from locating device **56** and position sensor **58**, may be configured to execute instructions stored on computer readable medium to perform various methods of excavation planning and control for machines **42**. Such excavation planning methods may include, among other things, determining a required number, location, size, and/or shape of a plurality of cuts into an intended work surface **68** at calibration site **40**. Additional excavation planning methods may include grouping the cuts into a plurality of spaced apart locations known as "slots," determining a spacing between, a size of, and/or a trajectory of such slots, and determining a sequence of particular cuts that should be excavated in order. Excavation planning methods may further include determining a number of passes through each sequence required to accomplish an excavation phase, and determining a number of phases required to complete an excavation plan. Worksite management system **38** may store in memory various excavation plans for accomplishing modifications and/or construction of calibration site **40** for possible calibration-related needs of machine **10**.

Exemplary operation of worksite management system **38** is discussed below with reference to FIG. **3**, FIG. **4** and FIG. **5**.

## INDUSTRIAL APPLICABILITY

The systems and methods of the present disclosure may be applicable to any mobile machine utilizing a vehicle model to control movement of the machine. Machine **10** may store in memory multiple vehicle models corresponding to different worksite conditions. For example, machine **10** may store different vehicle models for dry road conditions, icy road conditions, and wet road conditions. When the worksite conditions change on worksite **11**, the appropriate vehicle model may be calibrated and used to control machine **10**.

Machine **10** may also store in memory one or multiple vehicle models corresponding to different machine kinematics and/or dynamics, and one or more such vehicle models may be calibrated during operation. For example, machine **10** may store different vehicle models for articulated steering,

front and/or rear wheel steering, and/or skid steering dynamics. During operation on the worksite **11**, on-board controller **20** may select the appropriate vehicle model based on which calibrated vehicle model most closely predicts vehicle operation, and the selected vehicle model may be used to control machine **10**.

In exemplary embodiments, the vehicle model used by machine **10** may be initially calibrated, and subsequently recalibrated, after a period of use so when the vehicle model is used by on-board controller **20** the predicted performance of machine **10** may be approximately equal to the actual performance of machine **10**. If the predicted performance (for example, the movements and/or activity) of machine **10** is substantially similar to the actual performance of machine **10**, then machine **10** will function efficiently within worksite **11**.

FIG. **3** illustrates an exemplary method of how worksite management system **38** may coordinate the calibration needs of machines **10** at worksite **11**. Either worksite management system **38** or on-board controller **20** may monitor operating conditions of machine **10**, including various loads, operating states, orientations, and/or positions of machine **10**, for which calibration has either not yet been completed or for which one or more vehicle models associated with machine **10** require recalibration.

On-board controller **20** may identify when a need for calibration of an aspect of a vehicle model of machine **10** exists. In particular, at regular intervals, on-board controller **20** may use the vehicle model to predict a performance parameter of machine **10**. Regular intervals may include every few hours, every few months, or after machine **10** has been in operation for a particular number of hours. At step **305**, on-board controller **20** may compare a measured performance of machine **10** to a predicted (predicted by the vehicle model) performance of machine **10**. In addition to comparing measured and predicted performances at regular intervals, calibration-related needs of machine **10** may also be monitored. Such needs may be monitored at similar intervals described above with regard to the vehicle model and may be monitored by sensors **18** and **22**. Examples of when calibration-related needs may arise may include when wear of components on machine **10** is suspected, when a configuration of machine **10** is changed, or after machine **10** has been repaired. In each of these situations, machine **10** need not be sent to a specialized testing facility or to a remote location relative to worksite **11** in order to update the vehicle model used by on-board controller **20** to control machine **10**. There may be opportunities to calibrate the vehicle model by directing machine **10** to an appropriate calibration site **40** within worksite **11**.

At step **310**, on-board controller **20** may determine if a measured performance parameter value of machine **10** is substantially equal to a corresponding predicted performance parameter value of machine **10**. On-board controller **20** may make this determination by comparing data input from sensors **18** and **22** with data supplied by the vehicle model. Sensors **18** and **22** may provide measured values indicative of and/or quantifying the aforementioned operating conditions of machine **10**. The vehicle model may provide predicted values corresponding to each of the operating conditions. If the measured values are substantially equal to the predicted values (Step **310**—Yes), or if the difference between them does not exceed a threshold amount, machine **10** may continue to function with no identified need of calibration. The threshold amount may be an amount the actual performance of machine **10** is permitted to deviate from the predicted performance of machine **10** without requiring updating of the vehicle model. For example, the vehicle model may predict that based on the load weight, speed, orientation, and other

conditions for machine 10, the expected stopping distance of machine 10 is 50 feet. The actual stopping distance for machine 10 under these conditions, however, may be measured by sensors 18, 22 as 54 feet. When the threshold amount is set, for example, to be a percentage of the predicted amount, such as 10%, or when the threshold is set to be a particular braking distance, such as 5 feet, the difference between the predicted and actual performance of machine 10 does not exceed the threshold amount in the above example. Thus, in this example, machine 10 may continue to operate normally and efficiently without calibrating the vehicle model. As will be described below, one or more mathematical expressions or equations may be derived to account for the differences between the predicted and actual performance values, and the vehicle model may be adjusted in view of these expressions or equations when the difference exceeds the threshold amount.

If the measured values are not substantially equal to the predicted values (Step 310—No), and/or their difference is outside a predetermined threshold, on-board controller 20 may determine that the vehicle model is in need of calibration, or recalibration. In particular, at step 320, on-board controller 20 may determine the calibration need and communicate the calibration need to worksite management system 38.

Once on-board controller 20 has identified a particular vehicle model as needing to be calibrated, and a particular aspect of the vehicle model has been identified as needing to be calibrated, on-board controller 20 may communicate this information to worksite management system 38 (step 320) via an electronic signal and/or an otherwise wireless signal. Upon receipt of the signal from on-board controller 20, worksite management system 38 may search its memory for machine-specific templates. Machine-specific templates may include data associated with machine conditions, road conditions, and/or road geometries required for the accurate calibration of the specific vehicle model related to the operation of the particular machine 10. At step 325, worksite management system 38 may search for the machine-specific template, identify the calibration conditions required to calibrate a particular vehicle model, and may search a memory for a calibration site 40 where machine 10 may perform the needed calibration. In particular, worksite management system 38 may search a memory for a calibration site 40 that matches the calibration need of machine 10. In such embodiments, data related to the road conditions and geometries of worksite 11 may be stored within a memory of worksite management system 38. The data stored in the memory may identify, among other things, the percent grade and distance of an incline in between various locations on worksite 11. The memory may also store data related to open, or otherwise undeveloped, areas of autonomous worksite 11 where new roads and/or calibration sites 40 may be constructed. At step 325, worksite management system 38 may evaluate the available calibration sites 40 by quantifying each, based on their characteristics, and identifying a match where the difference between the compared values falls within a predetermined range. The numeric value of an available calibration site 40 may be referred to as a suitability index. Worksite management system 38 may identify which calibration sites 40 have suitability indices that fall within the predetermined range. Quantifying a calibration need and/or a calibration site 40 may include assigning numerical values to various characteristics. In this way, the closeness of a match involving multiple characteristics may be gauged by a calculated percent. For example, a 95% match between a calibration requirement and the suitability index of a calibration site 40 may be deemed to be adequate and may be recognized by worksite management

system 38 as a candidate match that may be pursued. If a number of candidate calibration sites 40 fall within the predetermined threshold (having a percent match of at least 95% for the present example) worksite management system 38 may automatically select the candidate calibration site 40 with the highest, or closest, match.

At step 330, worksite management system 38 may determine if a calibration site 40 matching the calibration need of machine 10 exists within worksite 11. If worksite management system 38 determines that a calibration site 40 matching the calibration need of machine 10 does exist (Step 330— Yes) within worksite 11, then worksite management system 38 may direct machine 10 to the matching calibration site 40 for calibration (Step 340). Worksite management system 38 may direct machine 10 to perform the required calibration multiple times so as to confirm that the calibration was performed correctly.

To calibrate the vehicle model at step 340, the actual performance values of machine 10 for the variety of loads, states, and conditions may be compared to the corresponding performance values predicted by the uncalibrated vehicle model, and the uncalibrated vehicle model may be adjusted based on results of those comparisons. Autonomously calibrating an aspect of the vehicle model may include adjusting a parameter value associated with the aspect of the vehicle model to be approximately equal to a corresponding value associated with an actual performance of the machine. For example, during the calibration process machine 10 may be loaded to a certain weight, and with a certain load distribution, and may be directed to proceed relatively straight (for example, at a steering angle of about 0 degrees) on a relatively flat surface (for example, such that the roll and pitch of the machine are each about 0 degrees). Braking distance may then be measured under these conditions. For each speed at which the actual braking distance of machine 10 is determined (measured by sensors 18, 22), the uncalibrated vehicle model may be used to predict a corresponding braking distance based on the same load weight and distribution, steering angle, orientation, and the like. Comparisons of the actual and predicted braking distance values may be made, such as by on-board controller 20 or another processor. The vehicle model may be adjusted or calibrated based on results of the comparisons, such that the braking distances predicted by using the vehicle model may be substantially equal to the actual braking distances as measured by sensors 18, 22. For example, one or more mathematical expressions or equations may be derived to account for differences between expected and actual values. Similar comparisons may be made for various other combinations of conditions under which the actual performance of machine 10 is determined, so that the calibrated vehicle model may accurately predict the performance of machine 10 on worksite 11, including at loads, states, and conditions under which machine 10 was not directly tested.

In exemplary embodiments, it may be necessary or desired that worksite management system 38 direct machine 10 to multiple calibration sites 40 within worksite 11 in order to address each of the road geometry and road condition-related calibration needs of machine 10. In such embodiments, worksite management system 38 may generate a calibration plan or "calibration roadmap" designating a route by which machine 10 may visit one or more calibration sites 40 within worksite 11. Worksite management system 38 may consider a number of different variables when creating a calibration roadmap for machine 10. For example, worksite management system 38 may account for the time of day, and the traffic congestion that is characteristic of any particular time of day, and plan the calibration routes to be as time efficient as

possible by avoiding high traffic areas and other potential points of concern at worksite **11**. Additionally, worksite management system **38** may identify candidate calibration paths that are near a normal travel route of machine **10**. A normal travel route of machine **10** may include a route that machine **10** would ordinarily take in attending to its assigned work tasks.

With continued reference to FIG. **3**, if a suitable calibration site **40** cannot be identified by worksite management system **38** (Step **330**—No) worksite management system **38** may proceed to step **350**. At step **350**, worksite management system **38** may determine whether a site within worksite **11** would match the calibration need of machine **10** if relatively minor modifications were made to the site. In particular, worksite management system **38** may determine if worksite **11** includes a calibration site **40** having a characteristic corresponding to an aspect of the vehicle model in need of calibration, and that calibration of the aspect of the vehicle model requires modifying the characteristic of calibration site **40**. Identifying such a potential site may follow a similar process to that of Step **330** where the process of matching calibration needs with available potential calibration sites **40** involves quantifying each, based on their characteristics, and identifying a match where the difference between the compared values falls within a predetermined range. Alternatively, a candidate site for modification may be identified by its percentage match with the outstanding calibration need of machine **10**. Matches which result in quantitative values outside the predetermined range may be assumed to require modifications that are not relatively minor.

If such a candidate calibration site **40** is identified (Step **350**—Yes), various conditions and/or geometries of the road and/or terrain at the selected candidate calibration site may be modified. For example, at step **360**, worksite management system **38** may direct one or more machines **42** to make necessary modifications to the selected candidate calibration site so the selected candidate calibration site matches the calibration need of machine **10**. In particular, worksite management system **38** may identify the one or more aspects of the vehicle model on the particular machine **10** in need of calibration. Based on the identified aspects, worksite management system **38** may direct one or more machines **42** to create/modify conditions at the selected site so that the identified aspects of the vehicle model can be calibrated at the selected site. In such embodiments, machines **42** may be configured to modify various road geometries that may include curvatures, banks, grades, slaloms, road widths, and lane changes. Machines **42** may also be configured to modify variations of road conditions that may include dry, semi-wet, wet, very wet, icy, gravelly, and bumpy. One or more machines **42** may be dispatched and controlled by worksite management system **38** to make the required modifications in road geometry and condition at the selected calibration candidate site. Worksite management system **38** may coordinate multiple machines **42** working simultaneously at the same calibration site **40**. After the selected candidate calibration site is modified, worksite management system **38** may direct machine **10** to the modified site for calibration of the vehicle model (Step **365**).

Machines **42** may also load machines **10** when the calibration needs of machines **10** further include a load condition. Worksite management system **38** may direct machines **42** to load machines **10** with a load corresponding to the load condition prior to directing machines **10** to calibration site **40**.

If a suitable candidate site for modification is not identified (Step **350**—No), worksite management system **38** may proceed to step **370** where worksite management system **38** may

determine if space exists within worksite **11** for construction of a site matching the calibration needs of machine **10**. If such a space is found (Step **370**—Yes), similar to Step **360**, worksite management system **38** may direct machines **42** to the selected space to construct (as opposed to modify an existing calibration site **40** as in Step **360**) a site matching the calibration need of machine **10** (Step **380**). At step **380**, one or more machines **42** may be dispatched and controlled by worksite management system **38** to construct the customized calibration site **40** with the road geometries and conditions required for calibration of the vehicle model. In exemplary embodiments, construction of a new calibration site **40** may be similar to the process described above with respect to step **360**. Worksite management system **38** may direct machines **42** to construct a calibration site that matches the calibration need of machine **10** (Step **380**). At step **385**, worksite management system **38** may direct machine **10** to the newly constructed calibration site **40** for calibration of the vehicle model.

If an open space does not exist within worksite **11** for construction of a site matching the calibration needs of machine **10** (Step **370**—No), worksite management system **38** may log the data regarding the calibration need in memory for reassessment at a later time (Step **390**). The logged data may be stored for use when additional space at worksite **11** becomes available. For example, when worksite **11** expands, or a previously needed calibration site **40** is no longer needed, worksite management system **38** may revisit the logged data and reassess the opportunity to modify an existing calibration site **40**, or to create a new calibration site **40** to match the calibration needs of machine **10**. In the meantime, worksite management system **38** may reassign machine **10** to a new work task that does not require a work operation corresponding to the aspect of the vehicle model in need of calibration (Step **395**). In an alternate embodiment, worksite management system **38** may modify how machine **10** is allowed to operate. For example, if a needed calibration relates to a particular travel speed of machine **10** worksite management system may limit the travel speed of machine **10** such that machine **10** will not reach the particular travel speed for which calibration is required. In this way, rather than reassign machine **10** to a new work task, machine **10** may be able to continue performing its original work task within the limitations established by worksite management system **38**.

FIG. **4** illustrates another exemplary method of how worksite management system **38** may coordinate the calibration needs of machine **10** at worksite **11**. In the exemplary method of FIG. **4**, machine **10** may be programmed to automatically alert worksite management system **38** as to when a calibration and/or recalibration need exists. Additionally, machine **10** may be programmed to alert worksite management system **38** as to which calibration needs exist at which times. Steps **425** to **495** of FIG. **4** may be identical to the analogous steps **325** to **395** of FIG. **3**.

The calibration needs of machine **10**, and all data related to the calibration needs of machine **10**, may be stored in a memory within, or associated with, on-board controller **20**. On-board controller **20** may communicate the calibration needs related to machine **10** to worksite management system **38** via a signal.

Once on-board controller **20** has identified a particular vehicle model as needing to be calibrated, and a particular aspect of the vehicle model has been identified as needing to be calibrated, on-board controller **20** may communicate this information to worksite management system **38** (step **420**) via an electronic signal and/or an otherwise wireless signal. Upon receipt of the signal from on-board controller **20**, worksite management system **38** may search its memory for

machine-specific templates. Machine-specific templates may include data associated with machine conditions, road conditions, and/or road geometries required for the accurate calibration of the specific vehicle model related to the operation of the particular machine **10**. At step **425**, worksite management system **38** may search for the machine-specific template, identify the calibration conditions required to calibrate a particular vehicle model, and may search a memory for a calibration site **40** where machine **10** may perform the needed calibration. In particular, worksite management system **38** may search a memory for a calibration site **40** that matches the calibration need of machine **10**. In such embodiments, data related to the road conditions and geometries of worksite **11** may be stored within a memory of worksite management system **38**. The data stored in the memory may identify, among other things, the percent grade and distance of an incline in between various locations on worksite **11**. The memory may also store data related to open, or otherwise undeveloped, areas of worksite **11** where new roads and/or calibration sites **40** may be constructed. At step **425**, worksite management system **38** may evaluate the available calibration sites **40** by quantifying each, based on their characteristics, and identifying a match where the difference between the compared values falls within a predetermined range. The numeric value of an available calibration site **40** may be referred to as a suitability index. Worksite management system **38** may identify which calibration sites **40** have suitability indices that fall within the predetermined range. Quantifying a calibration need and/or a calibration site **40** may include assigning numerical values to various characteristics. In this way, the closeness of a match involving multiple characteristics may be gauged by a calculated percent. For example, a 95% match between a calibration requirement and the suitability index of a calibration site **40** may be deemed to be adequate and may be recognized by worksite management system **38** as a candidate match that may be pursued. If a number of candidate calibration sites **40** fall within the predetermined threshold (having a percent match of at least 95% for the present example) worksite management system **38** may automatically select the candidate calibration site **40** with the highest, or closest, match.

At step **430**, worksite management system **38** may determine if a calibration site **40** matching the calibration need of machine **10** exists within worksite **11**. If worksite management system **38** determines that a calibration site **40** matching the calibration need of machine **10** does exist (Step **430**—Yes) within worksite **11**, then worksite management system **38** may direct machine **10** to the matching calibration site **40** for calibration (Step **440**). Worksite management system **38** may direct machine **10** to perform the required calibration multiple times so as to confirm that the calibration was performed correctly.

To calibrate the vehicle model at step **440**, the actual performance values of machine **10** for the variety of loads, states, and operating conditions may be compared to the corresponding performance values predicted by the uncalibrated vehicle model, and the uncalibrated vehicle model may be adjusted based on results of those comparisons. Operating conditions of machine **10** may include a travel speed of the machine, a steering rate of the machine, a braking rate of the machine, a weight hauled by the machine, a weight distribution of a load hauled by the machine, an orientation of the machine, a geographical location of the machine, and a heading of the machine. Autonomously calibrating an aspect of the vehicle model may include adjusting a parameter value associated with the aspect of the vehicle model to be approximately equal to a corresponding value associated with an actual

performance of the machine. For example, during the calibration process machine **10** may be loaded to a certain weight, and with a certain load distribution, and may be directed to proceed relatively straight (for example, at a steering angle of about 0 degrees) on a relatively flat surface (for example, such that the roll and pitch of the machine are each about 0 degrees). Braking distance may then be measured under these conditions. For each speed at which the actual braking distance of machine **10** is determined (measured by sensors **18**, **22**), the uncalibrated vehicle model may be used to predict a corresponding braking distance based on the same load weight and distribution, steering angle, orientation, and the like. Comparisons of the actual and predicted braking distance values may be made, such as by on-board controller **20** or another processor. The vehicle model may be adjusted or calibrated based on results of the comparisons, such that the braking distances predicted by using the vehicle model may be substantially equal to the actual braking distances as measured by sensors **18**, **22**. For example, one or more mathematical expressions or equations may be derived to account for differences between expected and actual values. Similar comparisons may be made for various other combinations of conditions under which the actual performance of machine **10** is determined, so that the calibrated vehicle model may accurately predict the performance of machine **10** on worksite **11**, including at loads, states, and conditions under which machine **10** was not directly tested.

In exemplary embodiments, it may be necessary or desired that worksite management system **38** direct machine **10** to multiple calibration sites **40** within worksite **11** in order to address each of the road geometry and road condition-related calibration needs of machine **10**. In such embodiments, worksite management system **38** may generate a calibration plan or "calibration roadmap" designating a route by which machine **10** may visit one or more calibration sites **40** within worksite **11**. Worksite management system **38** may consider a number of different variables when creating a calibration roadmap for machine **10**. For example, worksite management system **38** may account for the time of day, and the traffic congestion that is characteristic of any particular time of day, and plan the calibration routes to be as time efficient as possible by avoiding high traffic areas and other potential points of concern at worksite **11**. Additionally, worksite management system **38** may identify candidate calibration paths that are near a normal travel route of machine **10**. A normal travel route of machine **10** may include a route that machine **10** would ordinarily take in attending to its assigned work tasks.

With continued reference to FIG. **4**, if a suitable calibration site **40** cannot be identified by worksite management system **38** (Step **430**—No) worksite management system **38** may proceed to step **450**. At step **450**, worksite management system **38** may determine whether a site within worksite **11** would match the calibration need of machine **10** if relatively minor modifications were made to the site. In particular, worksite management system **38** may determine if worksite **11** includes a calibration site **40** having a characteristic corresponding to an aspect of the vehicle model in need of calibration, and that calibration of the aspect of the vehicle model requires modifying the characteristic of calibration site **40**. Identifying such a potential site may follow a similar process to that of Step **430** where the process of matching calibration needs with available potential calibration sites **40** involves quantifying each, based on their characteristics, and identifying a match where the difference between the compared values falls within a predetermined range. Alternatively, a candidate site for modification may be identified by

its percentage match with the outstanding calibration need of machine 10. Matches which result in quantitative values outside the predetermined range may be assumed to require modifications that are not relatively minor.

If such a candidate calibration site 40 is identified (Step 450—Yes), various conditions and/or geometries of the road and/or terrain at the selected candidate calibration site may be modified. For example, at step 460, worksite management system 38 may direct one or more machines 42 to make necessary modifications to the selected candidate calibration site so the selected candidate calibration site matches the calibration need of machine 10. In particular, worksite management system 38 may identify the one or more aspects of the vehicle model on the particular machine 10 in need of calibration. Based on the identified aspects, worksite management system 38 may direct one or more machines 42 to create/modify conditions at the selected site so that the identified aspects of the vehicle model can be calibrated at the selected site. In such embodiments, machines 42 may be configured to modify various road geometries that may include curvatures, banks, grades, slaloms, road widths, and lane changes. Machines 42 may also be configured to modify variations of road conditions that may include dry, semi-wet, wet, very wet, icy, gravelly, and bumpy. One or more machines 42 may be dispatched and controlled by worksite management system 38 to make the required modifications in road geometry and condition at the selected calibration candidate site. Worksite management system 38 may coordinate multiple machines 42 working simultaneously at the same calibration site 40. After the selected candidate calibration site is modified, worksite management system 38 may direct machine 10 to the modified site for calibration of the vehicle model (Step 465).

Machines 42 may also load machines 10 when the calibration needs of machines 10 further include a load condition. Worksite management system 38 may direct machines 42 to load machines 10 with a load corresponding to the load condition prior to directing machines 10 to calibration site 40.

If a suitable candidate site for modification is not identified (Step 450—No), worksite management system 38 may proceed to step 470 where worksite management system 38 may determine if space exists within worksite 11 for construction of a site matching the calibration needs of machine 10. If such a space is found (Step 470—Yes), similar to Step 460, worksite management system 38 may direct machines 42 to the selected space to construct (as opposed to modify an existing calibration site 40 as in Step 460) a site matching the calibration need of machine 10 (Step 480). At step 480, one or more machines 42 may be dispatched and controlled by worksite management system 38 to construct the customized calibration site 40 with the road geometries and conditions required for calibration of the vehicle model. In exemplary embodiments, construction of a new calibration site 40 may be similar to the process described above with respect to step 460. Worksite management system 38 may direct machines 42 to construct a calibration site that matches the calibration need of machine 10 (Step 480). At step 485, worksite management system 38 may direct machine 10 to the newly constructed calibration site 40 for calibration of the vehicle model.

If an open space does not exist within worksite 11 for construction of a site matching the calibration needs of machine 10 (Step 470—No), worksite management system 38 may log the data regarding the calibration need in memory for reassessment at a later time (Step 490). The logged data may be stored for use when additional space at worksite 11 becomes available. For example, when worksite 11 expands, or a previously needed calibration site 40 is no longer needed,

worksite management system 38 may revisit the logged data and reassess the opportunity to modify an existing calibration site 40, or to create a new calibration site 40 to match the calibration needs of machine 10. In the meantime, worksite management system 38 may reassign machine 10 to a new work task that does not require a work operation corresponding to the aspect of the vehicle model in need of calibration (Step 495). In an alternate embodiment, worksite management system 38 may modify how machine 10 is allowed to operate. For example, if a needed calibration relates to a particular travel speed of machine 10 worksite management system may limit the travel speed of machine 10 such that it will not reach the particular travel speed for which calibration is required. In this way, rather than reassign machine 10 to a new work task, machine 10 is able to continue performing its original work task within the limitations established by worksite management system 38.

FIG. 5 illustrates an exemplary worksite map 510 that worksite management system 38 may generate. Worksite management system 38 may generate worksite map 510 as a function of the above-described memory searching and data analyzing techniques, and may provide operators and/or managers of worksite 11 with recommendations as to where to direct machine 10 to perform a single calibration or multiple calibrations. In particular, during step 325 in FIG. 3 and during step 425 in FIG. 4, worksite management system 38 may search a memory for calibration sites 40 within worksite 11 that match a calibration need, or a plurality of calibration needs, related to the vehicle model of machine 10. During step 325 and/or step 425, and using data stored within the memory, worksite management system 38 may generate worksite map 510 which may display the results of the search performed by worksite management system 38 for calibration sites 40 that match the calibration needs of the vehicle model of machine 10. Additionally, worksite map 510 may display recommendations as to which calibration sites 40 would provide the most time and resource-efficient opportunity for making the necessary vehicle model calibration.

Worksite map 510 may include a depiction of various haul roads 520 and/or various zones within worksite 11. Such zones may include, for example, a loading zone 530 and a dumping zone 540. Worksite map 510 may illustrate, for example, loading zone 530, dumping zone 540, and/or other zones within worksite 11 being interconnected by one or more haul roads 520. Worksite map 510 may also include a recommended calibration site 560 (depicted by circles in FIG. 5) as well as a second recommended calibration site 565 (depicted by circles in FIG. 5). Recommended calibration site 560 may be associated with one calibration need associated with the vehicle model of machine 10, whereas second recommended calibration site 565 may be associated with a second calibration need associated with the vehicle model of machine 10. In the exemplary embodiment, recommended calibration site 560 and second recommended calibration site 565 may differ so as to address different calibration needs, or they may share similar features and present an operator and/or manager of worksite 11 with multiple options for addressing the same calibration need. Worksite map 510 may also include additional recommended calibration sites if additional calibration needs related to machine 10 exist. Worksite map 510 may include one or more recommended calibration sites and/or paths in need of modification 555 (depicted by squares in FIG. 5). As described above, recommended calibration sites and/or paths in need of modification 555 may include areas that would suffice as calibration sites 40 if modifications were made to them. Recommended calibration sites and/or paths in need of modification 555 may include

stretches of haul roads **520** in need of repair. As machines **10** traverse haul roads **520**, and detect road conditions via sensors **18** (S, M, L) and **22**, machines **10** may alert worksite management system **38** as to instances of slippage or other phenomena that may be indicative of a haul road **520** or calibration site **40** in need of repair and/or modification. Worksite map **510** may further include one or more calibration exclusion zones **550** (depicted by the letter "x" in FIG. **5**). Calibration exclusion zones **550** may include high traffic areas, for example, an intersection or a work zone such as a loading or dumping area. Calibration exclusion zones **550** may also include stretches of haul roads **520** that may be dangerous for certain machines **10** to traverse. Calibration exclusion zones **550** may be areas within worksite **11** that the operator selects and/or otherwise identifies. Further, calibration exclusion zones **550** may include areas that are designated for the calibration of other aspects of other vehicle models for other machines **10**. Worksite management system **38** may identify recommended calibration site **560**, second recommended calibration site **565**, recommended calibration site and/or path in need of modification **555**, and calibration exclusion zones **550** based on real time data, as well as landscape and/or road geometry-related data, related to worksite **11**. Worksite map **510** may include any one of a number of various topographical features **570** that may indicate various details of the landscape of worksite **11**. For example, one topographical feature **570** of worksite map **510** may indicate an elevation of a particular zone or segment of haul road **520**.

Worksite management system **38** may provide worksite map **510** to a manager of worksite **11** via an electronic or wireless signal, and worksite map **510** may be displayed on a monitor or other medium. Worksite map **510** may be color coded. Recommended calibration routes **580** may be identified as a first color. Recommended calibration sites and/or paths in need of modification **555** may be identified as a second color. Calibration exclusion zones **550** may be identified as a third color. For example, rather than displaying circles, worksite management system **38** may depict recommended calibration site **560** and second recommended calibration site **565** as green colored segments on worksite map **510**. Rather than displaying squares, worksite management system **38** may depict recommended calibration sites and/or paths in need of modification **555** as yellow colored segments on worksite map **510**. Rather than displaying the letter "x", worksite management system **38** may depict calibration exclusion zones **550** as red colored segments on worksite map **510**. Worksite management system **38** may present all the options related to recommended calibration sites **560**, **565**, recommended calibration sites and/or paths in need of modification **555**, and calibration exclusion zones **550** to a manager of worksite **11**. Once presented with all the aforedescribed options associated with a calibration need the manager of worksite **11** may add additional information to worksite map **510**. For example, if the manager is aware of areas within worksite **11** that should be avoided when planning a calibration route, and these calibration exclusion zones **550** were not identified by worksite management system **38**. the manager may manually designate the areas as such on worksite map **510**.

As previously described, worksite management system **38** may generate a calibration plan or "calibration roadmap" designating a recommended calibration route **580** by which machine **10** may efficiently visit one or more calibration sites **40** within worksite **11** while circumventing calibration exclusion zones **550**. Recommended calibration site **560** and second recommended calibration site **565** may correspond to calibration sites **40** as described above. As previously

described, worksite management system **38** may consider a number of different variables when generating recommended calibration route **580** for machine **10**. For example, worksite management system **38** may account for the time of day, and the traffic congestion that may be characteristic of a particular time of day, and plan calibration routes that take the least amount of travel time by avoiding high traffic areas and other potential points of concern at worksite **11**. The high traffic areas and other potential points of concern at worksite **11** may be designated on worksite map **510** as calibration exclusion zones **550**. Additionally, worksite management system **38** may plan recommended calibration route **580** to be near a normal travel route of machine **10**. A normal travel route of machine **10** may include a route that machine **10** would ordinarily take in attending to its assigned work tasks.

In an exemplary embodiment, a manager and/or operator of worksite **11** may select a particular machine **10** and/or vehicle model on the display monitor, and worksite management system **38** may display a map of worksite **11** illustrating, in real time, the calibration sites available for calibration of the particular machine **10** and/or vehicle model. Worksite management system **38** may also provide the manager a summary or list of calibration and/or time-sensitive maintenance needs of machine **10**. The manager may request from worksite management system **38** a proposed calibration site and or path. Worksite management system **38** may then illustrate available and proposed areas to meet the calibration needs of the particular machine **10** and/or vehicle model. Worksite management system **38** may illustrate multiple calibration maps for a plurality of various machines on the same display such that the manager may see an overall summary of calibration occurring within worksite **11**, in real time.

Worksite management system **38** may simultaneously schedule and coordinate the calibrations of a plurality of machines **10** with varying calibration needs. For example, worksite management system **38** may schedule the calibration of a first machine **10** at a certain time, and may delay the needed calibration of a second machine **10** to occur after the completion of the calibration of the first machine **10**. The scheduling function of worksite management system **38** may incorporate work task prioritization, traffic patterns, blasting, and other events and factors into the scheduling of calibration of different machines **10**. Calibration schedules generated by worksite management system **38** may be subject to approval by a site manager.

Use of the disclosed worksite map **510** may provide numerous advantages to operators and/or managers of worksite **11**. For example, by identifying recommended calibration sites **560**, calibration exclusion zones **550**, recommended calibration sites and/or paths in need of modification **555**, and/or recommended calibration routes **580**, worksite management system **38** provides recommendations to a worksite manager for proposed paths to accomplish a needed calibration in a time efficient fashion. Additionally, worksite map **510** may enable machine **10** to expend less fuel than perhaps would otherwise be required by limiting the distance machine **10** is required to travel to calibrate its vehicle model, and by limiting the amount of time machine **10** may be delayed in traffic congestion.

Use of the disclosed calibration system to initially calibrate and subsequently recalibrate the vehicle model may provide numerous advantages. As discussed above, because calibration and recalibration occur on the worksite **11**, delays associated with adjustment of the vehicle model at a calibration site removed from worksite **11** may be avoided. Further, the vehicle model of machine **10** may be more accurately cali-

brated and recalibrated as compared to known calibration processes, since machine **10** may be calibrated using actual conditions on worksite **11**.

Use of the disclosed worksite management system **38** to autonomously coordinate the modification of calibration sites **40** for calibration of the vehicle model may also provide numerous advantages. In addition to avoiding delays associated with conducting calibration at sites removed from worksite **11**, worksite management system **38** may enable a more efficient use of both time and resources by creating and/or modifying calibration sites **40** within worksite **11**. In particular, worksite management system **38** may facilitate the creation and/or modification of calibration sites **40** near work sites and travel routes of machines **10** such that machines **10** are calibrated in a time and travel efficient manner. Furthermore, by coordinating and performing modifications to calibration sites **40** autonomously, the human resources required for controlling operation of worksite **11** may be reduced.

It will be apparent to those skilled in the art that various modifications and variations can be made to the vehicle model calibration processes of the present disclosure. Other embodiments of the described methods and systems will be apparent to those skilled in the art from consideration of the specification and practice of the vehicle model calibration processes disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope of the disclosure being indicated by the following claims and their equivalents.

What is claimed is:

**1**. A method of calibrating a vehicle model used to autonomously control a machine on a worksite, the method comprising:

measuring, using a sensor, a first value indicative of an operating condition of the machine;

predicting, using a controller, a second value indicative of the operating condition, using the vehicle model;

determining a difference between the first value and the second value;

identifying calibration conditions required to calibrate the vehicle model when the difference is greater than a predetermined threshold;

searching for calibration sites where the vehicle model can be calibrated based on the identified calibration conditions;

selecting a calibration site from the calibration sites based on a suitability index representing characteristics of the calibration site;

directing the machine to the selected calibration site; and

calibrating the vehicle model at the selected calibration site, wherein calibrating the vehicle model includes adjusting the vehicle model such that the second value predicted using the vehicle model is approximately equal to the first value measured using the sensor.

**2**. The method according to claim **1**, wherein searching for the calibration sites further includes searching a memory storing data associated with the calibration sites, the data including the calibration conditions.

**3**. The method according to claim **1**, wherein selecting the calibration site includes identifying the calibration site that has a suitability index within a predetermined range, and that has the closest match to a calibration requirement of the machine.

**4**. The method according to claim **1**, wherein directing the machine to the selected calibration site includes measuring real-time traffic conditions associated with the worksite and selecting a route to the selected calibration site based on the real-time traffic conditions.

**5**. The method according to claim **1**, wherein the operating condition includes at least one of a travel speed of the machine, a steering rate of the machine, a braking rate of the machine, a weight hauled by the machine, a weight distribution of a load hauled by the machine, an orientation of the machine, a geographical location of the machine, and a heading of the machine.

**6**. The method according to claim **1**, further including:

determining that no calibration site matching a calibration requirement of the machine exists within the worksite; and

determining whether a site within the worksite would match the calibration requirement of the machine if modifications were made to the site.

**7**. A method of calibrating a vehicle model used to autonomously control a machine on a worksite, the method comprising:

measuring, using a sensor, a first value indicative of an operating condition of the machine;

predicting, using a controller, a second value indicative of the operating condition, using the vehicle model;

determining a difference between the first value and the second value;

providing a signal to a worksite management system in response to determining the difference between the first value and the second value is greater than a predetermined threshold, wherein the worksite management system is disposed remote from the machine and the signal is indicative of an aspect of the vehicle model that is in need of calibration;

identifying calibration conditions required to calibrate the vehicle model when the difference is greater than a predetermined threshold;

searching for calibration sites where the vehicle model can be calibrated based on the identified calibration conditions;

selecting a calibration site from the calibration sites based on a suitability index representing characteristics of the calibration site;

autonomously directing the machine to the selected calibration site in response to receipt of the signal by the worksite management system; and

calibrating the vehicle model at the selected calibration site, wherein calibrating the vehicle model includes adjusting the vehicle model such that the second value predicted using the vehicle model is approximately equal to the first value measured using the sensor.

**8**. The method according to claim **7**, wherein searching for the calibration sites further includes searching a memory associated with the worksite management system, the memory storing data associated with the calibration sites, the data including the calibration conditions.

**9**. The method according to claim **7**, wherein selecting the calibration site includes identifying the calibration site that has a suitability index within the predetermined range, and that has the closest match to a calibration requirement of the machine.

**10**. The method according to claim **7**, wherein measuring the first value includes providing a signal indicative of the first value from the sensor to a controller on the machine.

**11**. The method according to claim **10**, further including:

predicting, with the controller, the second value;

determining, with the controller, the difference between the first value and the second value; and

providing, with the controller, the signal indicative of the aspect of the vehicle model in need of calibration to the worksite management system.

**12**. The method according to claim **7**, wherein directing the machine to the selected calibration site includes measuring, with the worksite management system, real-time traffic conditions associated with the worksite and selecting a route to the calibration site based on the real-time traffic conditions.

**13**. The method according to claim **7**, wherein the operating condition includes at least one of a speed of the machine, a steering angle of the machine, a weight hauled by the machine, a weight distribution of a load hauled by the machine, an orientation of the machine, a geographical location of the machine, and a heading of the machine.

**14**. The method according to claim **1**, further including:

determining, with the worksite management system, that no calibration site matching a calibration requirement of the machine exists within the worksite, and

determining whether a site within the worksite would match the calibration requirement of the machine if modifications were made to the site.

**15**. A method of calibrating a vehicle model used to autonomously control a machine on a worksite, the method comprising:

storing, in a memory, calibration needs of the machine, a calibration need being determined based on a difference between a first value measured using a sensor and a second value predicted using the vehicle model;

scheduling, using a controller, the occurrence of the calibration needs;

providing a signal to a worksite management system in response to determining that the calibration need exists,

wherein the signal is indicative of an aspect of the vehicle model that is in need of calibration;

searching for calibration sites where the aspect of the vehicle model can be calibrated based on the identified calibration conditions;

selecting a calibration site from the calibration sites based on a suitability index representing characteristics of the calibration site;

generating a map of the worksite identifying the selected calibration site for calibration of the vehicle model; and

calibrating the aspect of the vehicle model at the selected calibration site, wherein calibrating the aspect of the vehicle model includes adjusting the vehicle model such that the second value predicted using the vehicle model is approximately equal to the first value measured using the sensor.

**16**. The method according to claim **15**, wherein generating a map of the worksite includes illustrating the selected calibration site, and a recommended calibration route from a present location of the machine to the selected calibration site.

**17**. The method according to claim **16**, further including identifying a calibration exclusion zone, and illustrating the calibration exclusion zone on the map of the worksite with the recommended calibration route.

**18**. The method according to claim **17**, further including a landscape feature associated with the worksite, and illustrating the landscape feature on the map of the worksite with the recommended calibration route.

* * * * *

# CERTIFICATE OF CORRECTION

PATENT NO.   : 9,182,760 B2            Page 1 of 1
APPLICATION NO. : 13/712417
DATED     : November 10, 2015
INVENTOR(S)   : Braunstein et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page, Column 1, Item 72 (Inventors), line 3, delete "Swissvalve, PA" and insert
-- Swissvale, PA --.

Signed and Sealed this
Eighteenth Day of October, 2016

Michelle K. Lee
*Director of the United States Patent and Trademark Office*